

Cloud and Precipitation community input to the 2017-2027 Earth Science Decadal Survey RFI drawn from several workshops (URL <http://pmm.nasa.gov/CAPPM>)

## 1. What are the key challenges for Earth System Science in the coming decade?

The 21<sup>st</sup> century poses extreme challenges for the sustainable management of the Earth's water resources at all levels from the local to the global scale. The international climate community through the World Climate Research Programme (WCRP) has identified the issues underlying water availability, climate extremes and cloud influences on climate as three of the grand challenges facing both our understanding of and ability to adapt to climate change (<http://wcrp-climate.org/grand-challenges>). Three basic questions posed by WCRP are how will the availability of fresh water change in the coming decades, what is the predictability of changes in the frequency and intensity of precipitation extremes at seasonal to decadal time scales, and how does convection shape cloud feedbacks? *Since water is necessary for all life on Earth, knowing where, when and how clouds form, and whether they precipitate or not, is vital for all civilization.* Central to these themes require better predictions of water at all scales. This requires a paradigm shift away from our current practices that largely observe "states" to future observing strategies that can deliver information on both states and "processes". Processes here refer to the production of precipitation within clouds that are in turn driven by dynamics that range in scale from the convective to the synoptic. Thus it becomes *essential to understand at both the local and global scale the underlying cloud processes (via measurable proxies such as ice microphysics and vertical velocities) that result in precipitation for improving the next generation of climate and numerical weather prediction (NWP) models.* As the resolutions of these climate models increase over time to be able to explicitly represent cloud and convective processes, it is equally imperative to plan for timely observations to constrain, evaluate and define these processes to produce more accurate predictions of the water cycle.

## 2. Why are these challenge/questions timely?

Climate models, which couple precipitation to the global changes in energy fluxes, show relatively small increasing trends in global precipitation in a manner consistent with observations. At the same time, these models show relatively little skill reproducing regional precipitation changes. This problem is often attributed to the poor representation of clouds and convective systems, as well as the scale interactions that are ultimately responsible for the water budgets at local scales. The range of scales involved in these processes has led the community to push for resolutions that can explicitly capture clouds in climate models. Computing capabilities have increased significantly so that global cloud-resolving scales are now becoming feasible and are being implemented in short-term climate simulations of months to years with anticipation to century+ simulations likely over the next decade. Despite successful missions such as TRMM, GPM, and CloudSat, that excel at measuring current cloud structures, measurements to simultaneously constrain and evaluate cloud and precipitation processes in high-resolution models do not currently exist, ultimately resulting in large uncertainties in models. Providing data to inform global cloud-resolving model development is thus timely.

Furthermore, elucidating cloud and precipitation processes is an essential step in Earth system science. By processes, we mean the fundamental mechanisms governing the evolution of embryonic cloud droplets and ice crystals to precipitation sized particles, and the updrafts that support this growth, mechanisms that should be valid no matter what changes in the Earth's circulation are predicted. We thus envision a process-oriented approach that allows for cloud microphysics and dynamics to be understood and parameterized for the different cloud systems developing in the various environmental regimes around the globe. Measured statistics are desperately needed that couple in-cloud vertical velocities to resulting hydrometeor types and their profiles in order to improve the dynamical and microphysical parameterizations, and the feedbacks between them, in cloud-resolving models. While the cloud and precipitation communities have traditionally been separate, they are now coming together through this process-level view.

### 3. Why are space-based observations fundamental?

It is simply impossible to create cloud and precipitation process statistics with ground or aircraft measurements. Reliable statistics that cover the entire spectrum of processes over a heterogeneous Earth will require satellite-based global measurements. Processes are a function of meteorology and environmental conditions within a regime. Many of these regimes are in very remote and hostile locations (high latitudes, remote oceans, etc.) so that even collecting data in brief field programs is prohibitive. Instead, process questions may inevitably require that the spaceborne component be linked with well thought out and consistent experiments to support process modeling over short time scales.

Because aerosols, clouds and precipitation are inherently linked, missions such as ACE or their new incarnation after the 2017 Decadal survey are essential investments to increase the value of datasets for understanding cloud and precipitation processes. Indeed, the science proposed herein includes a subset of ACE's objectives. Furthermore, connections between the water, hydrological, and radiative budget cycles necessitate that ancillary observations of these Earth system components would be extremely valuable for advancing the scientific and societal benefits of a cloud-precipitation measurement mission.

#### a. Are existing/planned programs sufficient to make substantial progress on the science?

NASA's Precipitation Measurement Missions (TRMM and GPM), A-Train Missions, Cloud and Radiation Program, Weather Focus Area, and mission concept working groups such as ACE provide strong scientific leadership and instrumentation heritage for space-based observations of clouds and precipitation. Together with the planned EarthCARE mission, these observations provide vital data for climate studies. Additional investments, both to enhance processes understanding (via multi-frequency/Doppler radars and wideband radiometers) and maintain data records, offer a way to make substantial progress on the cloud and precipitation process challenges by observing critical measurements of cloud parameter evolution and additional process information and placing these into a longer term context.

b. How does this science link space-based observations with other observations to increase the value of data?

Lower resolution but broad scale satellite measurements over the globe establishes statistically robust interrelationships between processes and environment necessary to improve weather and climate models. However, high-resolution and intensive but localized/sporadic observations of weather processes from ground or suborbital assets provide details that are not otherwise attainable from space.

The value of combined cloud and precipitation data will be improvements to the fundamental understanding of real cloud and precipitation systems, ultimately leading to perfected parameterizations for predictions about changing fresh water supplies in both weather and climate models. Delivering 4-dimensional measurements of the space-time evolution of the properties of global clouds and precipitation will help to quantify regional and global water cycle processes and serve to provide a better understanding of storm structures, water/energy budgets, the atmospheric movement of water and interactions between precipitation and other environmental and climate parameters. Tying together the storm dynamics with the microphysics will lead to significant advances in relating cloud processes to environmental influences and regional sensitivities.

c. What are the anticipated scientific and societal benefits?

These cloud and precipitation measurements, while principally designed to advance our confidence in the hydrologic predictions of any future climate, will clearly also lead to advancements in applications such as: predicting high-impact natural hazard events such as floods, droughts, hurricanes and snowstorms; improving climate prediction through better understanding of surface water fluxes, soil moisture storage, cloud/precipitation microphysics and latent heat release in the atmosphere to improve Earth system modeling and analysis; and advancing NWP skills through more accurate and frequent measurements of cloud and precipitation vertical property profiles together with better quantitative error characterizations and data assimilation systems. Knowledge would also be gained in topics such as the evolution of circulations like the MJO that depend upon the dynamic coupling of cloud scales, monsoons, orographic systems, mid-latitude cyclonic storms and processes that determine the severity of precipitating weather systems.

d. Who are the science communities that would be involved?

Scientists from NASA, JPL, and universities and other government and international agencies were directly involved in our cloud and precipitation workshops (as listed at URL <http://pmm.nasa.gov/CAPPM>). Other scientists would include members from the cloud/radiative and precipitation communities; aerosol communities; land surface (soil moisture, vegetation, agriculture, etc.) communities; weather-related natural hazard communities; as well any scientist with water related research. Specifically, the Water Resources and the Weather Focus community workshops mention cloud and precipitation data

as essential

([http://science.nasa.gov/media/medialibrary/2015/08/03/Weather\\_Focus\\_Area\\_Workshop\\_Report\\_2015.pdf](http://science.nasa.gov/media/medialibrary/2015/08/03/Weather_Focus_Area_Workshop_Report_2015.pdf), <https://eos.org/meeting-reports/satellite-data-for-water-resources-management>).

Given the fundamental importance of precipitation measurements, and the legacy of prior missions, a cloud and precipitation mission will likely include the involvement of foreign partners in contributing to important mission elements.

*In closing, coupled measurements bring together the cloud and precipitation scientists from both the observational and modeling communities to provide guidance to models with respect to precipitating weather systems – how they form, how they evolve and how they dissipate, such that these clouds can be parameterized not just in today's models, but in future models.*